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Solar Energy System Performance Evaluation

HOGATE'S RESTAURANT
Washington, D.C.
June through August, 1978

U.S. Department of Energy

National Solar Heating and Cooling Demonstration Program

National Solar Data Program

SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

HOGATE'S RESTAURANT
WASHINGTON, DC

JUNE THROUGH AUGUST, 1978

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NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under a specific format. For example, this report for the Hogate's Restaurant project site is designated as SOLAR/2028-78/14. The elements of this designation are explained in the following illustration:

SOLAR/2028-78/14

Prepared for the National Solar Data Program

Report type Designation

Demonstration Site Number

Year

- Demonstration Site Number:

  Each project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

- Report Type Designation:

  This number identifies the type of report, e.g.,

  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December)

  - Solar Energy System Performance Evaluations are designated by the number 14.

  - Solar Project Descriptions are designated by the number 50

  - Solar Project Cost Reports are designated by the number 60

These reports are disseminated through the U. S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy in accordance with the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to assist in establishment of a viable solar energy industry and to stimulate its growth to achieve a substantial reduction in fossil fuel consumption through widespread use of solar heating and cooling applications. The International Business Machines Corporation is contributing to this overall goal by monitoring, analyzing, and reporting system performance of solar energy systems through the National Solar Data Program. Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- System Performance Evaluation

All reports issued by the National Solar Data Program for the Hogate's Restaurant solar energy system are listed in Section 6.

This System Performance Evaluation report is a product of the National Solar Data Program. Evaluation reports are periodically issued to document results from analysis of a specific solar energy system's operational performance during the period covered by the report. The information presented in this report has been generated from monthly performance data collected at the specific site. These data include system description, operational characteristics and capabilities as well as the results of the evaluation of actual performance. Each parametric value presented as characteristic of this system's performance represents over 8,000 discrete measurements obtained monthly through the National Solar Data Network.

Acknowledgments are extended to the personnel of Hogate's Restaurant for their cooperation in providing information and help in resolving on-site problems.

2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation report presents a summary of the June through August, 1978 operation of the Hogate's Restaurant solar energy system. This system is designed to provide hot water on demand for the kitchen facilities located at Hogate's Restaurant. Presented are results of an evaluation of measured system performance and a comparison of measured climatic data with long term average conditions. Performance evaluations of each major subsystem are also presented.

Measurement data used [1-3]* were collected through the National Solar Network [4] for the period June 1978 through August 1978. System performance data are provided through the National Solar Data Network via the IBM developed Central Data Processing System [5]. The Central Data Processing System supports the daily collection and analysis of data from instrumented solar energy systems located throughout the country. These data are summarized into monthly performance reports which form the common basis used for system evaluation.

This report includes: a brief system description, review of actual system performance during the report period, analysis of performance based on evaluation of climatic, load and operational conditions, and an overall discussion of the results of analysis.

The solar energy system at Hogate's operated satisfactorily for the reporting period which was June through August, 1978. The average incident solar energy was 260 million Btu per month of which 90 million Btu were collected resulting in a collector array efficiency of 34 percent. Solar energy collection and utilization are approximately in phase at Hogate's Restaurant. This, coupled with the high rate of water consumption of 7,000 gallons per day, results in a 97 percent storage tank efficiency. The average monthly thermal load is 130 million Btu of which 63 percent is satisfied by the solar energy system.

* Numbers in brackets designate references listed in Section 6.

3. SYSTEM DESCRIPTION SUMMARY

Hogate's Restaurant (located in Washington, DC) has 6,254 square feet of flat plate collectors used to support energy requirements for a hot water system. The restaurant requires approximately 7,000 gallons of hot water each day between 4 AM and 2 AM. This hot water is used by the restaurant's kitchen facilities and must be supplied at 150°F. The solar energy system is a retrofit, and as such, the collectors face southwest instead of ideally facing south. The solar collector loop uses a mixture of 60% propylene glycol and 40% water as the heat transfer fluid. The potable water supply is isolated from the heat transfer fluid by a liquid to liquid heat exchanger. The collection and transfer of solar energy is controlled by the activation of two sets of pumps. Referring to Figure 3-1, when the difference between control temperature measurements located near temperature sensors T102 and T205 exceeds an "activate" setting in the controller, the primary pump of the (P1,P2) pair is turned on. The other pump is a backup pump which will start automatically if the primary pump fails. These pumps alternately change roles and are interlocked to prevent both from running simultaneously. The second set of pumps (P3,P4) is similarly configured and will be activated whenever set (P1,P2) is turned on. Solar heated water is stored in two 5,000 gallon tanks. Additional heating of service hot water is accomplished by a 960,000 Btu/hr gas fired boiler.

The solar energy system has been designed for three modes of operation:

Mode 1 - Hot Water Demand - When there is a hot water demand and solar radiation is insufficient for operating the collector, cold water from the inlet is directed through valves V6 and V7, through tanks T2 and T1, to the boiler where it is heated, if required, to 150°F.

Mode 2 - Collector to Storage with Hot Water Demand - This mode is invoked when there is sufficient solar energy to operate the collector and there is a demand for hot water. The primary pump of the (P3,P4) pair is also turned on causing water from the cold water supply to flow through the heat exchanger to tank 1. The preheated water in tank 1 is then available to the load. This mode is terminated when the temperature difference between control temperature measurements drops below a deactivation setting in the controller, the demand for hot water is satisfied or if the temperature of tank T1 exceeds 180°F. The temperature monitoring instrumentation is located between T102 and T205 shown in Figure 3-1.

Mode 3 - Regenerate - This mode is invoked when there is no hot water demand but there is sufficient solar energy for collector operation. Water is circulated from tank T2 through the heat exchanger to tank T1 and finally back to tank T2. This mode can be terminated either by an insufficient solar radiation condition or by the temperature of the water in tank T1 exceeding 180°F.

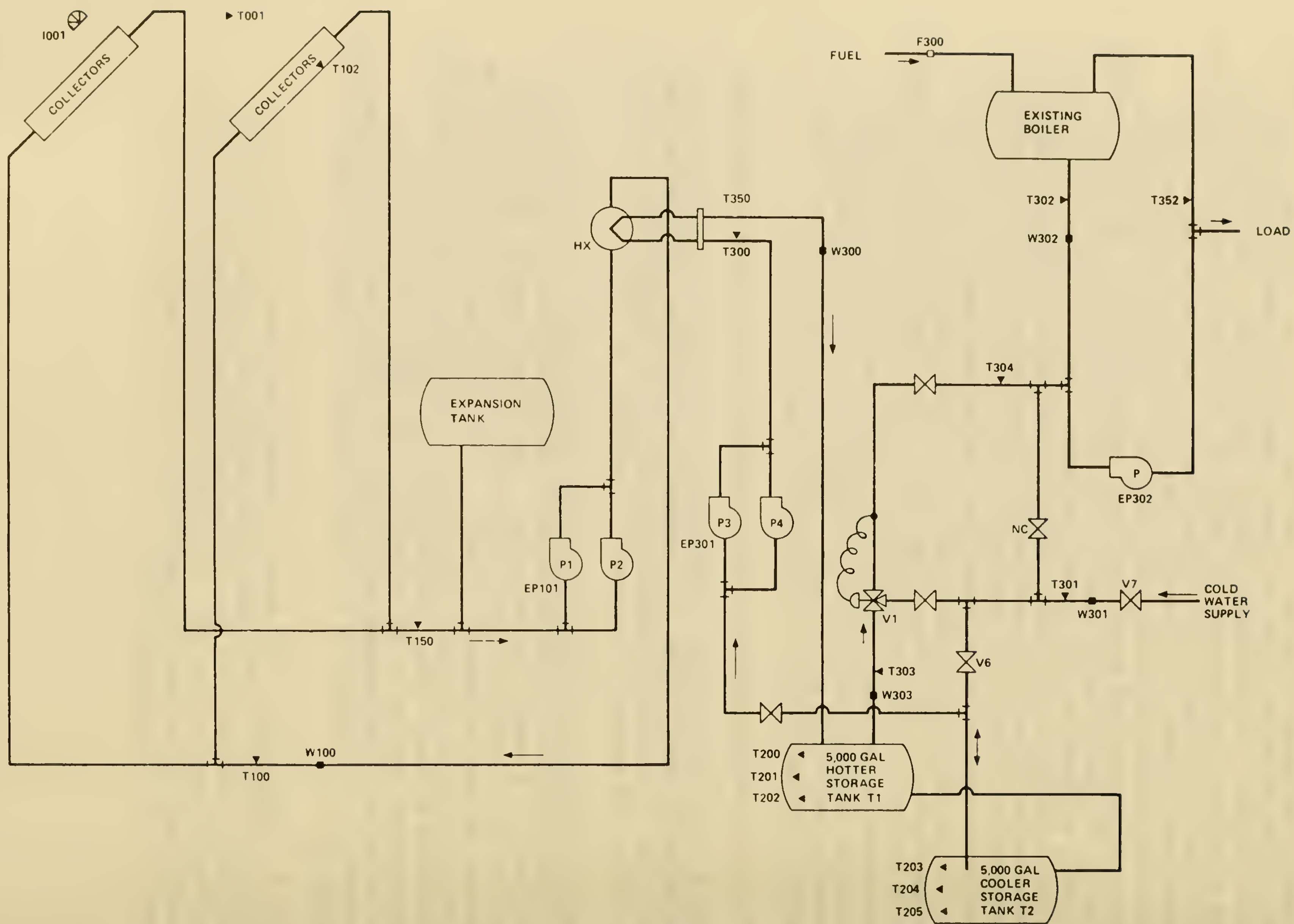

Figure 3-1. HOGATE'S RESTAURANT SOLAR ENERGY SYSTEM SCHEMATIC

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Hogate's Restaurant solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [6]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

Data from monitoring instrumentation colocated with the solar energy system is collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each component subsystem. Definitions of the evaluation parameters are provided in Appendix A. The equations used are given in Appendix B.

Each month a summary of overall performance of the Hogate's Restaurant site and a detailed subsystem analysis is published. Monthly reports for the period covered by this System Performance Evaluation, June through August, 1978, are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

5. PERFORMANCE ASSESSMENT

The performance of the Hogate's Restaurant solar energy system has been evaluated from June through August 1978. Two perspectives have been utilized for this assessment. The first looks at the overall system in which the total solar energy delivered to the loads, the amount of solar energy used by the hot water subsystem, and the percentage of the hot water subsystem load provided by solar energy have been presented. The other perspective is a more in depth look at the performance of individual subsystems. Details relating to the performance of the collector array and storage subsystems are presented first. This is followed by details pertaining to the hot water subsystem. In addition, the total amount of energy consumed by the hot water subsystem, both solar and auxiliary thermal, is shown so that some insight into the energy requirements of the subsystem may be obtained.

The performance assessment of any solar energy system is highly dependent on the prevailing climatic conditions at the site during the period of performance. The original design of the system is generally based on the long term averages for available insolation and temperature. Deviations from these long term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long term averages for critical climatic parameters has been provided.

5.1 Climatic Conditions

Monthly values of the total solar energy incident in the plane of the collector array and the average outdoor temperature measured at the Hogate's Restaurant site during the report period are presented in Table 5.1-1.

Also presented in Table 5.1-1 are long term average monthly values for these climatic parameters. Data for long term incident solar energy per unit area are estimates based on the Climatic Atlas of the United States [7]. These estimates use the horizontal data given in the reference to provide average values for the 55 degree angle of the Hogate's Restaurant collector array. All other long term average climatic data were taken from the National Oceanic and Atmospheric Administration Summary [8].

Measured incident solar energy values for Hogate's Restaurant during the summer months, depicted in Table 5.1-1, are lower than the long term average values. The measured insolation was 85 percent of the average long term insolation for the months of June, July and August. June had the highest with 90 percent of the average long term incident solar energy.

Ambient temperatures for June, July and August show only minor deviations from the normal ambient temperature expected during this period. The average for the reporting period was 77.3°F versus the normal of 75°F.

TABLE 5.1-1

CLIMATIC CONDITIONS

Month	Incident Solar Energy Per Unit Area (55° Tilt) (Btu/Ft^2)		Ambient Temperature (°F)	
	Measured	Long Term Average	Measured	Long Term Average
Jun 78	49,211	49,130	76	73
Jul 78	40,499	49,340	77	77
Aug 78	39,398	47,414	79	75
Total	129,108	145,884	-	-
Average	43,036	48,628	77	75

5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy applied to the system load. The total system load is the sum of the energy requirements, both solar and auxiliary thermal, for each subsystem. The portion of the total load provided by solar energy is defined as the solar fraction of the load. This solar fraction is the measure of performance for the solar energy system when compared to the design or expected solar contribution.

The thermal performance of the Hogate's Restaurant solar energy system is presented in Table 5.2-1.

TABLE 5.2-1

SYSTEM THERMAL PERFORMANCE

Month	Total Solar Energy to Load (Million Btu)	Solar Energy Used Hot Water (Million Btu)	Hot Water Solar Fraction (Percent)	
Jun 78	93.73	93.73	63	
Jul 78	80.29	80.29	65	
Aug 78	81.30	81.30	61	
Total	255.32	255.32	-	
Average	85.11	85.11	63	

During the report period, Hogate's solar energy system used an average of 85 million Btu of solar energy per month. This is approximately 63 percent of the hot water load imposed by the Hogate's system during this reporting period.

The solar energy system at Hogate's Restaurant failed during the reporting period. The primary pump on the storage side of the heat exchanger failed because of a broken impeller. The system, however, recovered immediately by utilizing the backup pump.

5.3 Subsystem Performance

The performance of solar energy subsystems is evaluated by calculating a set of primary performance factors based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [6]. Data from monitoring instrumentation, personalized to the unique features of the site's solar energy system, are collected via the National Solar Data Network. These data are first formed into factors which show the hourly performance of each subsystem by summation or averaging techniques. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each subsystem.

These hourly performance parameters quantify the thermal performance of the system by measuring the energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

The energies transferred through the system are determined by applying the first law of thermodynamics to the appropriate instrumentation in the system. The form of the first law used in this process is

$$Q = \int_{t_1}^{t_2} \rho w \, \Delta h \, dt \qquad (1)$$

where:

Q = energy transferred, Btu

ρ = density of the transport fluid, lb_m/gal

w = volumetric flow rate of the transport fluid, gal/min

Δh = enthalpy change of transport fluid, Btu/lb_m

dt = time interval in minutes.

Thermal performance analysis of the solar energy system is predicated on the instrumentation available, component performance and operating accuracy constraints. This solar energy system can be envisioned as composed of three unique but mutually dependent components. These components are the collector array, the thermal storage tank and the hot water subsystem. The hot water subsystem consists of the load imposed by the system and the thermal contribution by the thermal storage tanks and gas fired boiler (auxiliary energy) to the system load.

The application of equation (1) to each of the components is accomplished by certain instrumentation which is illustrated in Table 5.3-1. Equation (1) also is applied to compute the thermal contribution to the system load through the use of auxiliary energy. The instrumentation used for the auxiliary thermal contribution is contained in Table 5.3-1. The actual solar fraction that was used to support system thermal load requirements is computed by the following equation:

$$S.F. = \frac{Q_s}{Q_s + Q_{at}} \qquad (2)$$

where:

S.F. = solar fraction (HWSFR)

Q_s = solar energy used to support the system thermal load (solar energy from storage) (HWSE)

Q_{at} = auxiliary energy used to support the system thermal load (auxiliary energy) (HWAT).

TABLE 5.3-1

INSTRUMENTATION USED FOR ENERGY CALCULATIONS

Energy	Flow	Density Reference	Enthalpy Change Reference
Solar Energy Collected	W100	T100	T100, T150
Solar Energy to Storage	W300	T350	T350, T300
Solar Energy from Storage	W301	T303	T301, T304
Auxiliary Energy	W302	T302	T302, T352

5.3.1 Collector Array Subsystem

Collector array performance is described by comparison of the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency, which may be expressed as

$$\eta_c = Q_s / Q_i \qquad (3)$$

where:

η_c = Collector Array Efficiency (CAREF)

Q_s = Collected Solar Energy is the thermal energy removed from the collector array by energy transport medium (SECA)

Q_i = Incident Solar Energy is the total solar energy incident on gross collector array area (SEA)

The gross collector array area is 6,254 square feet of flat plate collector. Measured monthly values of incident solar energy, collected solar energy, and collector array efficiency are presented in Table 5.3.1-1.

Evaluation of collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yields operational collector efficiency. operational collector efficiency, η_{co}, is computed as follows:

$$\eta_{co} = Q_s / (Q_{oi} \times \frac{A_p}{A_a}) \qquad (4)$$

where:

Q_s = Collected Solar Energy (SECA)

Q_{oi} = Operational Incident Energy is the amount of solar energy incident on the collector array during the time that the collector loop is operating and attempting to collect energy (SEOP)

A_p = Gross Collector Area (product of the number of collectors and the total area of the envelope of one unit) (GCA)

A_a = Gross Collector Array Area (total area perpendicular to the solar flux vector including all mounting, connecting and transport hardware) (GCAA)

TABLE 5.3.1-1

COLLECTOR ARRAY PERFORMANCE

Month	Incident Solar Energy (Million Btu)	Collected Solar Energy (Million Btu)	Collector Array Efficiency	Operational Incident Energy (Million Btu)	Operational Collector Efficiency
Jun 78	276.50	94.62	.34	213.37	.44
Jul 78	253.29	85.63	.34	196.41	.44
Aug 78	246.39	86.07	.35	190.23	.45
Total	776.18	266.32	-	600.01	-
Average	258.73	88.77	.34	200.00	.44

This latter efficiency term is not precisely the same as collector efficiency as represented by the ASHRAE Standard 93-77 [9]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the collector operational efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are also presented in Table 5.3.1-1.

Hogate's Restaurant solar energy system has two banks of flat plate collectors manufactured by Sunworks. The two banks contain 302 collector panels and have a gross area of 6,254 square feet. Referring to Table 5.3.1-1, the three month reporting period shown indicates that the average collector array efficiency was 34 percent. This figure is based on the gross collector area. Actually 33 panels were inoperative during this reporting period; therefore, the incident solar energy reported in Table 5.3.1-1 is approximately ten percent high and the collector array efficiency is approximately ten percent low. The collector array efficiency compares favorably with the results given in Figure 5.3.1-1, which presents a comparison of the actual performance of the collector array for the month of August to the performance prediction based on the linear instantaneous efficiency curve derived from single panel test data. The results presented in Figure 5.3.1-1 show that the actual performance was less than the predicted performance by ten percent. This ten percent deviation can be attributed to transient operational effects of the collector array and thermal losses from the collector manifold and headers.

Analysis for the month of June showed an energy imbalance between the collector loop and the storage tank; more energy was being stored than collected. Subsequent investigation indicated that the transport fluid, which should have been a solution of 60 percent propylene glycol and 40 percent water, had actually been diluted to 30 percent by the frequent addition of water. Since the specific heat of the transport fluid is used to compute the amount of energy collected, any variation from the specified propylene glycol solution can cause error in the computation of the amount of energy collected and the corresponding collector array performance factors. The difference between the actual and assumed specific heat of the transport fluid was ten percent. This difference was sufficient to cause the observed energy imbalance.

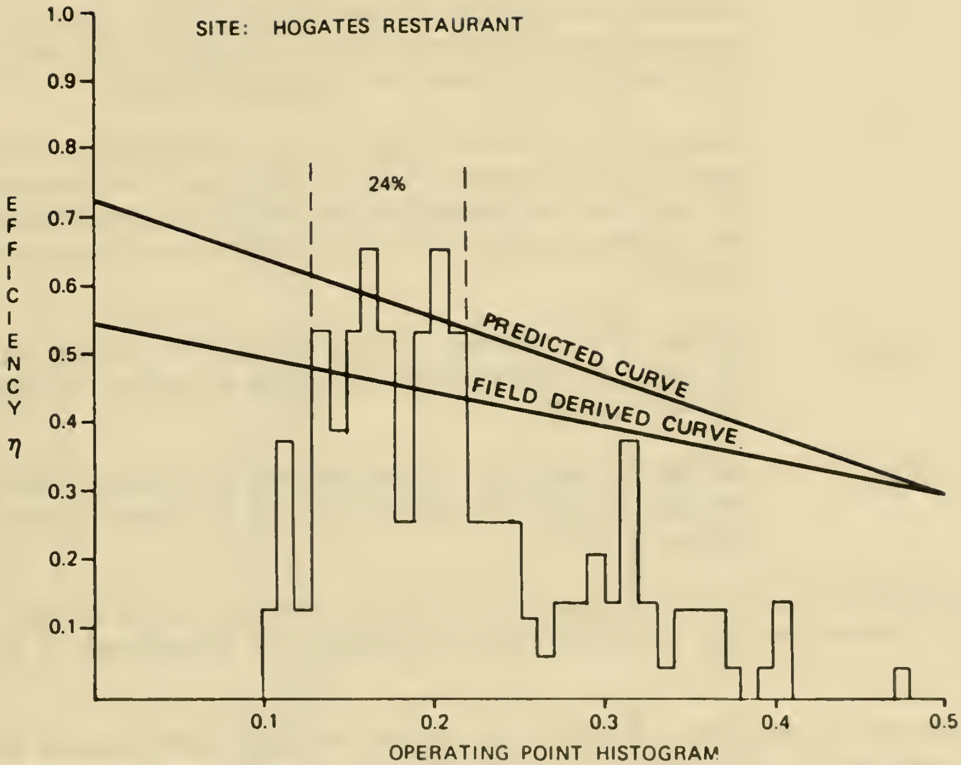

Figure 5.3.1-1. Operating Point Histogram

5.3.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency. This relationship is expressed by the equation:

$$\eta_s = (\Delta Q + Q_{so}) / Q_{si} \qquad (5)$$

where:

η_s = Storage Efficiency is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage (STEFF)

ΔQ = Change in Stored Energy is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value) (STECH)

Q_{so} = Energy from storage is the amount of energy extracted by the load subsystems from the primary storage medium (STEO)

Q_{si} = Energy to Storage is the amount of energy (both solar and auxiliary) delivered to the primary storage medium (STEI)

Measured monthly values of energy to storage, energy from storage, change in stored energy, and storage efficiency are presented in Table 5.3.2-1.

Evaluation of the Hogate's Restaurant system storage performance under actual transient system operation and climatic conditions can be performed using the parameters listed above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the derivation presented below.

The overall thermal properties of the actual storage subsystem design can be derived empirically as a function of storage average temperature for the reporting periods and the ambient temperature in the vicinity of the storage tank.

TABLE 5.3.2-1

STORAGE PERFORMANCE

Month	Energy To Storage (Million Btu)	Energy From Storage (Million Btu)	Change In Storage Energy (Million Btu)	Storage Efficiency	Storage Average Temperature (°F)	Effective Heat Loss Coefficient (Btu/Hr °F)
Jun 78	94.40	93.73	-0.33	.99	112	39
Jul 78	83.30	80.30	-0.59	.95	114	150
Aug 78	83.73	83.50	-1.80	.97	118	162
Total	261.96	257.53	-2.72	-	-	-
Average	87.32	85.84	-0.91	.97	115	117

An effective storage heat transfer coefficient for the storage subsystem can be defined as follows:

$$C = (Q_{si} - Q_{so} - \Delta Q_s) / [(\overline{T}_s - \overline{T}_a) \times t] \left(\frac{\text{Btu}}{°\text{F-hr}}\right) \qquad (6)$$

where:

C = Effective storage heat transfer coefficient

Q_{si} = Energy to Storage (STEI)

Q_{so} = Energy from Storage (STEO)

ΔQ_s = Change in Stored Energy (STECH)

$\overline{T}_s$ = Storage Average Temperature (TS)

$\overline{T}_a$ = Average Ambient Temperature in Vicinity (TE)

t = Number of hours in the month (HM)

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [10]. It has been calculated for each month in this report period and included, along with storage average temperature, in Table 5.3.2-1.

Measured monthly values of energy delivered to storage, energy extracted from storage, change in stored energy and storage efficiency are presented in Table 5.3.2-1. The storage efficiency recorded for this reporting period is approximately 97 percent. This storage efficiency is high because the losses from storage are small compared to the energy transferred to and from storage. This is expected because the energy collection and utilization are almost in phase and the energy is withdrawn from the tank as fast as it is deposited because of the continuous consumption of hot water.

5.3.3 Hot Water Subsystem

The system hot water load and the thermal contributions from the storage tanks and gas boiler describe the performance of the hot water subsystem. The hot water subsystem performance is determined by the comparison of solar energy used and auxiliary thermal energies used with the hot water load. Measured and expected monthly values of these performance factors are presented in Table 5.3.3-1. Also shown is the fraction of available solar energy provided to and used by the hot water subsystem. The expected hot water loads and solar fractions were determined using the f-Chart method [11] and are based on the measured climatic conditions at the site during the reporting period.

TABLE 5.3.3-1

HOT WATER SUBSYSTEM PERFORMANCE

Month	Hot Water Load		Energy Consumed		Solar Fraction (Percent)	
	Measured (Million Btu)	Expected (Million Btu)	Solar (Million Btu)	Auxiliary Thermal (Million Btu)	Measured	Expected
Jun 78	142.69	128.07	93.73	57.29	63.0	65.0
Jul 78	121.76	132.34	80.30	46.35	65.0	64.5
Aug 78	123.99	132.34	83.55	48.11	65.0	62.9
Total	388.44	392.75	257.58	151.75	-	-
Average	129.48	130.92	85.86	50.58	64.3	64.1

Referring to Table 5.3.3-1, the average hot water load for this reporting period of 130 million Btu per month agrees favorably with the expected load for this period of 131 million Btu per month. The measured hot water load was satisfied by using 86 million Btu of solar energy per month and 51 million Btu of auxiliary energy. This represents an average of 7 million Btu per month of energy losses from the hot water subsystem. These losses are due to normal transport losses of which the major part can be accounted for in the circulation loop which continually circulates water through a gas fired boiler to supply heated water on demand to the load.

The 86 million Btu of solar energy used each month to support the hot water subsystem constituted 64.3 percent of the system load. This compares favorably with the expected value of 64.1 percent for this reporting period. Therefore, it can be concluded that the Hogate's solar energy system is operating as expected. However, during the reporting period it was discovered that the auxiliary gas boiler's efficiency was well below what was expected.

Based on measurements of the gas input and the thermal output of the boiler during the reporting period, the efficiency of the boiler was found to be 25 percent. Contact with site personnel established that unburned gas could be detected coming from the gas fired boiler's exhaust. Subsequently the boiler was repaired. Since the unburned gas could not be taken into account when comparing the solar energy system operation to that of a conventional boiler system, a boiler efficiency of 50 percent was used for the computation of fossil fuel savings. The system achieved an average fossil fuel savings of 172 million Btu per month during this reporting period.

5.4 Operating Energy

Operating energy is defined as the energy used to provide for the transport of solar energy to the point of use. Total operating energy for the solar energy system at Hogate's Restaurant consists of electrical energy required to support the ECSS heat transfer loops and the amount of electrical energy required to support the subsystem, such as fans and pumps which do not affect the thermal state of the subsystem. Measurements of the monthly values of these performance factors are presented in Table 5.4-1.

The average monthly operating energy for the Solar Energy System at Hogate's Restaurant from June through August, 1978, was 3.13 million Btu. This provided for the collection and storage of 87.3 million Btu/month of solar energy and the delivery of 135 million Btu/month to the hot water subsystem.

TABLE 5.4-1

SYSTEM OPERATING ENERGY

Month	ECSS Operating Energy (Million Btu)	Operating Energy Hot Water (Million Btu)	Total System Operating Energy (Million Btu)
Jun 78	2.21	0.64	2.85
Jul 78	2.83	0.62	3.95
Aug 78	2.48	0.62	3.10
Total	7.52	1.88	9.90
Average	2.51	0.63	3.30

5.5 System Availability

The availability of a solar energy system is determined by the ability of its functional subsystems to perform their designed tasks when design operational conditions exist.

This may be expressed as:

$$\text{Availability} = \frac{\text{Solar Subsystem Equipment Operating Time}}{\text{Demand for Subsystem Time.}}$$

where:

Availability = 100 percent if the demand time is zero.

A subsystem is considered unavailable if a demand for its function exists, prevailing conditions meet appropriate prescribed criteria, and the subsystem fails to perform its function. Availability also indicates the degree to which a subsystem responds to those demands which it was intended to satisfy. Subsystem availability alone, rather than total system availability, is presented in this report as more than one subsystem could be expected to be operational at the same time and a composite availability factor would confuse the actual conditions of performance. Availability of the Hogate's Restaurant solar energy system as presented in this report is represented by the availability of its energy collection and storage subsystem and the solar portions of the hot water subsystem.

The Hogate's Restaurant energy collection and storage subsystem is considered available except for those times when the following conditions exist:

(1) The total solar energy incident on the gross collector array is less than 25 percent of its monthly average.

(2) The mass-weighted average temperature of the primary storage medium is less than its maximum allowable value.

(3) The solar energy incident on the collector array during the time that the collector loop is active is less than 25 percent of the incident solar energy.

The average energy collection and storage subsystem availability for the Hogate's Restaurant solar energy system was 100 percent for the period June through August, 1978.

The Hogate's Restaurant hot water subsystem is considered available except for those times when the following conditions exist:

(1) A hot water demand was encountered as indicated by hot water load. This is defined as the sum of the energy supplied by the solar energy system plus the energy supplied by auxiliary sources.

(2) No solar energy was used to attempt to satisfy the hot water load as indicated by solar energy used-hot water. This is defined as the amount of solar energy supplied to the hot water subsystem.

The hot water subsystem availability has been determined strictly on the solar energy available to supply the load. For this reporting period, solar energy has always been available for delivery to the system load. Since there are no known failures present in the hot water subsystem, the hot water subsystem is considered to have been available 100 percent of the time.

5.6 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet hot water demands rather than energy provided by auxiliary fuel sources. The conventional source of hot water has been taken to be the baseline system with savings being realized whenever solar energy was employed to supplant fossil fuel usage. Measured monthly values of fossil energy savings is estimated as the difference between fossil energy requirements of the alternative conventional system carrying the full load and the actual fossil energy consumed by the system. These savings figures are presented in Table 5.6-1. The electrical energy to support the subsystem, such as fans and pumps, is reprinted here from Table 5.4-1 since this quantity is not included in the subsystem energy savings and must be algebraically added to obtain the total savings.

The value of 1000 Btu/cubic foot has been used to convert the fossil savings from Btu to cubic feet. Table 5.6-1 expresses fossil savings in terms of both Btu and cubic feet. A conventional boiler with a burner efficiency of 50 percent has been assumed for every month in the reporting period except June. After the month of June, unburned gas was detected coming through the boiler vent. At this time a boiler efficiency of 50 percent was used to determine fossil savings. During the month of June, however, an efficiency of 25 percent was used which explains a hot water fossil savings figure for the month of June which is approximately double that recorded for the months of July and August. Consequently, the total savings figure recorded in Table 5.6-1 for the month of June is approximately 50 percent greater than the total savings figure recorded for July and August.

TABLE 5.6-1

ENERGY SAVINGS

Month	ECSS Operating Energy (Million Btu)	Hot Water Operating Energy (Million Btu)	Hot Water Fossil Savings (Million Btu)	Total Fossil Savings (Cubic Feet)	Total Savings (Million Btu)
Jun 78	2.21	0.64	374	374,000	374
Jul 78	2.83	0.62	160	160,000	156
Aug 78	2.48	0.62	167	167,000	163
Total	7.52	1.88	701	701,000	693
Average	2.51	0.63	234	234,000	231

The ECSS operating energy has averaged 3 percent of the collected solar energy throughout the reporting period.

Net savings have been realized every month throughout the reporting period. As illustrated in Table 5.3.3-1, each month has shown a consistently favorable solar energy fraction.

6. REFERENCES

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11. W. A. Beckman, S. A. Klein, and J. A. Duffie, Solar Heating Design by the f-Chart Method, John Wiley, New York, NY, (1977).

* Copies of these reports may be obtained from Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

APPENDIX A

DEFINITIONS OF PERFORMANCE FACTORS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total solar energy incident on the gross collector array area. This is the area of the collector array energy-removing aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY(SEA) is the total solar energy incident on the gross collector array area. This is the area of the collector array energy-removing aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- ECSS OPERATING ENERGY (CSOPE) is the electrical operating energy required to support the ECSS heat transfer loops.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow into and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary fossil fuel, and electrical auxiliary thermal energy, and the operating energy for the subsystem. In addition, the solar energy supplied to the subsystem, along with solar fraction, is tabulated.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- <u>AUXILIARY FOSSIL FUEL</u> (HWAF) is the amount of fossil fuel energy supplied directly to the subsystem.

- <u>ELECTRICAL ENERGY SAVINGS</u> (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- <u>FOSSIL ENERGY SAVINGS</u> (HWSVF) is the estimated difference between the fossil energy requirements of the alternative conventional system (carrying the full load) and the actual fossil energy requirements of the subsystem.

- <u>SUPPLY WATER TEMPERATURE</u> (TSW) is the average inlet temperature of the water supplied to the subsystem.

- <u>AVERAGE HOT WATER TEMPERATURE</u> (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.

- <u>HOT WATER USED</u> (HWCSM) is the volume of water used.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- <u>TOTAL INSOLATION</u> (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

- <u>AMBIENT TEMPERATURE</u> (TA) is the average temperature of the environment at the site.

- <u>WIND DIRECTION</u> (WDIR) is the average direction of the prevailing wind.

- <u>WIND SPEED</u> (WIND) is the average wind speed measured at the site.

- <u>DAYTIME AMBIENT TEMPERATURE</u> (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR HOGATE'S RESTAURANT

I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{Solar Energy Available} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

Where I001 is the solar radiation measurement provided by the pyranometer in BTU/ft^2-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time).

Similarly, the energy flow within a system is given typically by

$$\text{Collected Solar Energy} = \Sigma\ [\text{W100} \times \text{CP} \times \text{RHO} \times (\text{T150} - \text{T100})] \times \Delta\tau$$

Where W100 is the flow rate of the heat transfer fluid in gal/min, CP and RHO are the specific heat and density, and T100 and T150 are the temperatures of the fluid before and after passing through the heat exchanging component. Frequently this temperature difference is referred to as simply TD100. The product W100 x RHO is often combined and represented as M100.

For electrical power, a general example is

$$\text{ECSS Operating Energy} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

Where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and (3413) correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [6]. This document was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of operation of systems. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the twenty-four hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE - ALL UNITS ARE MILLION BTU UNLESS OTHERWISE SPECIFIED

- MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC (FIGURE 3-1)

SITE SUMMARY REPORT

INCIDENT SOLAR ENERGY

$= (1/60)\ \Sigma\ [I001 \times AREA] \times \Delta\tau$

INCIDENT SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT)

$= (1/60)\ \Sigma\ I001 \times \Delta\tau$

COLLECTED SOLAR ENERGY

$= \Sigma\ [M100 \times CP \times (T150 - T100)] \times \Delta\tau$

COLLECTED SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT)

$= \Sigma\ [M100 \times CP \times (T150 - T100)/AREA] \times \Delta\tau$

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

$= (1/60)\ \Sigma\ [T001] \times \Delta\tau$

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOADS/INCIDENT SOLAR ENERGY

ECSS OPERATING ENERGY

$= (56.88)\ \Sigma\ (EP101) \times \Delta\tau$

WHENEVER COLLECTORS ARE OPERATING

TOTAL SYSTEM OPERATING ENERGY

= ECSS OPERATING ENERGY + HOT WATER OPERATING ENERGY

TOTAL ENERGY CONSUMED

= AUXILIARY FOSSIL ENERGY + SYSTEM OPERATING ENERGY + SOLAR ENERGY COLLECTED

HOT WATER LOAD

= HOT WATER AUXILIARY THERMAL ENERGY + HOT WATER SOLAR ENERGY

TOTAL SYSTEM LOAD

= HOT WATER LOAD

HOT WATER SOLAR FRACTION (PERCENT)

$$= \frac{\text{HOT WATER SOLAR ENERGY}}{\text{HOT WATER SOLAR ENERGY + AUX THERMAL ENERGY}}$$

HOT WATER SOLAR ENERGY

$= \Sigma\ [M303 \times CP \times (T302 - T301)] \times \Delta\tau$

TOTAL SOLAR ENERGY USED

= HOT WATER SOLAR ENERGY

HOT WATER OPERATING ENERGY

$= 56.88\ \Sigma\ (EP301 + EP302 + 0.6 \times EP304)$

TOTAL OPERATING ENERGY

= ECSS OPERATING ENERGY + HOT WATER OPERATING ENERGY

HOT WATER AUXILIARY THERMAL ENERGY

$= \Sigma\ [M302 \times CP\ X\ (T352 - T302)] \times \Delta\tau$

TOTAL AUXILIARY THERMAL ENERGY

= HOT WATER AUXILIARY THERMAL ENERGY

HOT WATER AUXILIARY FOSSIL FUEL

= 4 x HOT WATER AUXILIARY THERMAL ENERGY

TOTAL AUXILIARY FOSSIL FUEL

= HOT WATER AUXILIARY THERMAL ENERGY

HOT WATER FOSSIL FUEL SAVINGS

= 2 x HOT WATER SOLAR ENERGY

TOTAL FOSSIL FUEL SAVINGS

= HOT WATER FOSSIL FUEL SAVINGS

SYSTEM PERFORMANCE FACTOR

= SYSTEM LOAD/(HOT WATER AUXILIARY FOSSIL + 3.33 x SYSTEM OPERATING ENERGY)

OPERATIONAL INCIDENT ENERGY

$= (1/60) \Sigma [I001 \times AREA] \times \Delta\tau$

WHENEVER COLLECTOR PUMP IS RUNNING

COLLECTOR ARRAY EFFICIENCY

= SOLAR ENERGY COLLECTED/INCIDENT SOLAR ENERGY

ENERGY TO STORAGE

$= \Sigma [M300 \times CP \times (T350 - T300)] \times \Delta\tau$

ENERGY FROM STORAGE

$= \Sigma [M303 \times CP \times (T303 - T301)] \times \Delta\tau$

CHANGE IN STORED ENERGY

$= STOCAP \times (TST \times RHO \times CP - TST_p \times RHO_p \times CP_p)$

Where the subscript p indicates values obtained from previous scans

STORAGE AVERAGE TEMP (DEGREES F)

$$= (1/60) \Sigma \frac{(T200 + T201 + T202 + T203 + T204 + T205)}{6} \times \Delta\tau$$

STORAGE EFFICIENCY

- (CHANGE IN STORED ENERGY + ENERGY FROM STORAGE)/ENERGY TO STORAGE

ECSS SOLAR CONVERSION EFFICIENCY

= SOLAR ENERGY TO LOADS/INDICANT SOLAR ENERGY

SUPPLY WATER TEMP (DEGREES F)

$$= (1/60)\ \Sigma\ T301\ \Delta\tau$$

HOT WATER AVG. TEMP (DEGREES F)

$$= (1/60)\ \Sigma\ T352$$

HOT WATER USED (GALLONS)

$$= \Sigma\ W301\ \Delta\tau$$

DAYTIME AMBIENT TEMP (DEGREES F)

$$= (1/360)\ \Sigma\ [T001)\ \times\ \Delta\tau$$

$\pm$ 3 HOURS FROM SOLAR NOON